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Citation
Lingam, Manasvi, and Abraham Loeb. 2017. "Fast Radio Bursts from Extragalactic Light Sails." The Astrophysical Journal 837 (2) (March 8): L23. doi:10.3847/2041-8213/aa633e.

Published Version
doi:10.3847/2041-8213/aa633e

Draft version January 5, 2017
Typeset using LaTeX **twocolumn** style in AASTeX61

FAST RADIO BURSTS FROM EXTRAGALACTIC LIGHT SAILS

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ABSTRACT

We examine the possibility that Fast Radio Bursts (FRBs) originate from the activity of extragalactic civilizations. Our analysis shows that beams used for powering large light sails could yield parameters that are consistent with FRBs. The characteristic diameter of the beam emitter is estimated through a combination of energetic and engineering constraints, and both approaches intriguingly yield a similar result which is on the scale of a large rocky planet. Moreover, the optimal frequency for powering the light sail is shown to be similar to the detected FRB frequencies. These 'coincidences' lend some credence to the possibility that FRBs might be artificial in origin. Other relevant quantities, such as the typical mass of the light sail, and the angular velocity of the beam, are also derived. By using the FRB occurrence rate, we infer upper bounds on the rate of FRBs from extragalactic civilizations in a typical galaxy. The possibility of detecting fainter signals is briefly discussed, and the wait time for an exceptionally bright FRB event in the Milky Way is estimated.

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1. INTRODUCTION

Ever since the first discovery of Fast Radio Bursts (FRBs) over a decade ago (Lorimer et al. 2007), there has been a great deal of interest in uncovering their origin. Currently, only 17 FRBs have been recorded, and a summary of their properties can be found in Petroff et al. (2016).[1] Hypotheses put forward for FRBs range from supramassive neutron stars (Falcke & Rezzolla 2014) to gamma-ray bursts (Zhang 2014) and stellar flares (Loeb et al. 2014). Regardless of their actual origin, it is now widely accepted that most FRBs are at cosmological distances (Thornton et al. 2013). The unusually high brightness temperature of FRB sources at cosmological distances, $\sim 10^{37}$ K, implies that their radio emission mechanism must be coherent (Katz 2016) as known to exist in pulsars or human-made radio transmitters. Despite the diversity of explanations advanced for FRBs, the possibility that they may be of artificial origin has not been investigated, except for a brief consideration in Luan & Goldreich (2014).

In this Letter, we examine the possibility that FRBs are artificial beams which have been set up as beacons, or for driving light sails. The idea that extraterrestrial civilizations may be using radio beams is certainly not a new one, as it dates back to the pioneering paper by Cocconi & Morrison (1959). This idea was quickly picked up and extended by researchers engaged in the Search for Extraterrestrial Intelligence (SETI), and an account of the progress in this field can be found in Drake & Sobel (1992); Tarter (2001); Webb (2015). In addition to the traditional, radio-based SETI, several other approaches have also been advanced for detecting alien civilizations (Dyson 1960; Schwartz & Townes 1961; Howard et al. 2004; Benford et al. 2010; Loeb & Turner 2012; Wright et al. 2014; Zackrisson et al. 2015).

The outline of the paper is as follows. In Section 2, we show that the parameters required for powering artificial beams are compatible with the FRB constraints. We also consider the possibility that the beams are being used to power light sails. We discuss the implications and predictions in Section 3, and summarize our main conclusions in Section 4.

2. COMPATIBILITY OF FAST RADIO BURSTS AND BEAMS

We start by examining whether some of the major FRB constraints are consistent with the assumption of artificial beams, and then explore the possibility that these beams may be used to power light sails.

2.1. *FRB constraints and requirements*

We begin by denoting the distance of the beam source from the Earth by r. One of the primary *observable* parameters for FRBs is the dispersion measure (DM), defined through a line-of-sight integral,

$$\mathrm{DM} = \int_0^r n_e(s)\, ds = \bar{n}_e r, \tag{1}$$

of the mean number density of free electrons $\bar{n}_e$. Ignoring contributions from the source, its host galaxy and the Milky Way, one may adopt the mean comoving electron density for the intergalactic medium (IGM), $\bar{n}_e \approx 2 \times 10^{-7}\,\mathrm{cm}^{-3}$ (Planck Collaboration et al. 2016; Fialkov & Loeb 2016). For simplicity, we shall assume henceforth that the FRB redshifts are < 1, and drop the redshift factors in the context of our order-of-magnitude estimates.

Most sources in the FRB catalog (Petroff et al. 2016) have DM values of order hundreds of cm^{-3} pc. Using equation (1), the distance can be estimated as,

$$r \sim 1\,\mathrm{Gpc} \left(\frac{\mathrm{DM}}{200\,\mathrm{cm}^{-3}\,\mathrm{pc}}\right) \left(\frac{\bar{n}_e}{2 \times 10^{-7}\,\mathrm{cm}^{-3}}\right)^{-1}. \tag{2}$$

The distance obtained by means of this simple relation is broadly consistent with more accurate estimates (Petroff et al. 2015, 2016).

Next, let us suppose that the beam has an angular width θ and a radiated (peak) power P. We may express the beam angle as some factor η times the minimum value set by the diffraction limit,

$$\theta = \eta \frac{c}{\nu D}, \tag{3}$$

where ν is the frequency of the radiation, D is the diameter of the beam emitter, and $\eta \geq 1$. The spectral flux density is given by,

$$S_\nu = \eta^{-2} \left(\frac{D}{cr}\right)^2 \alpha \varepsilon \nu P, \tag{4}$$

where $\alpha = d \ln S / d \ln \nu$ is the spectral index and ε is the radiative efficiency. We adopt $\varepsilon\alpha \sim 1$, thereby making the above formula identical to Luan & Goldreich (2014); this is a reasonable assumption since $\varepsilon < 1$ and $\alpha \sim \mathcal{O}(1)$ for FRBs (Katz 2016). One may invert this relation to solve for P noting that the characteristic values of 1 GHz and 1 Jy have been chosen for ν and S_ν respectively, based on the FRB catalog. This gives,

$$P \sim 10^{25}\,\mathrm{erg\,s^{-1}} \left(\frac{r}{1\,\mathrm{Gpc}}\right)^2 \left(\frac{\nu}{1\,\mathrm{GHz}}\right)^{-1} \left(\frac{S_\nu}{1\,\mathrm{Jy}}\right) \times \eta^2 \left(\frac{D}{3 \times 10^9\,\mathrm{cm}}\right)^{-2}, \tag{5}$$

where the value of D was normalized to the size of a large rocky planet (Winn & Fabrycky 2015) for reasons explained below.

[1] http://www.astronomy.swin.edu.au/pulsar/frbcat/

First, let us suppose that extraterrestrial civilizations adopt the strategy of harnessing solar power (Lubin 2016). Taking our own Sun as the reference, and using the present-day value of the solar constant, we find

$$P = 10^{25}\,\mathrm{erg\,s^{-1}}\left(\frac{D}{3\times10^{9}\,\mathrm{cm}}\right)^{2}. \tag{6}$$

Interestingly, equations (5) and (6) yield the same value of P for $D \sim 3\times10^9$ cm, assuming that all other quantities are held fixed at their characteristic values. In physical terms, it amounts to saying that the beam can be powered fully by solar power provided that its aperture is approximately this value.

The second way of deducing the characteristic value of D is as follows. As the aperture efficiency is ε, a fraction $(1-\varepsilon)$ would be dissipated. This amounts to a power per unit area of $(1-\varepsilon)\,P/D^2$ at the base of the emitter. If we assume that this excess heat is radiated away thermally, we get

$$\frac{(1-\varepsilon)\,P}{D^2} = \sigma T^4, \tag{7}$$

where T is the surface temperature of the beamer. If the value of T is too high, there may be structural damage. Hence, an upper bound on T translates to a lower bound on D. Inverting the above expression to find P, we obtain

$$P = 10^{25}\,\mathrm{erg\,s^{-1}}\left(\frac{1}{1-\varepsilon}\right)\left(\frac{D}{3\times10^{9}\,\mathrm{cm}}\right)^{2}\left(\frac{T}{373\,\mathrm{K}}\right)^{4}, \tag{8}$$

and a comparison with (5) and (6) reveals that the same power estimate is obtained for the choice of $D \sim 3\times10^9$ cm. This represents the *minimum* aperture diameter that is required to keep the system running. Note that the value of T has been normalized to the boiling temperature of water, since it is widely used as a coolant in many beamer designs (Weber et al. 1998).

Thus, we have shown that the characteristic value of $D \sim 3\times10^9$ cm is obtained in two very different ways - one is an energetic constraint whilst the other is derived from engineering considerations. This already constitutes a remarkable coincidence. But, what makes this value all the more unique is a third coincidence - this value is about 2.35 times the diameter of the Earth. In other words, the beam emitter is an object akin to that of a planet; more precisely, it lies fairly close to the boundary of super-Earths and mini-Neptunes (Lopez & Fortney 2014; Rogers 2015). Another possibility worth considering is that the emitter could have been fashioned along the lines of the Stapledon-Dyson sphere (Stapledon 1937; Dyson 1960).

2.2. *What is the purpose of these beams?*

The preceding discussion serves to illustrate the fact that some of the major observables for FRBs are consistent with the idea that they may be manifestations of extragalactic beams. However, this still fails to answer the important question of why they exist in the first place.

The first, and most immediate, possibility is that they serve the purpose of 'beacons', and are thus meant to broadcast the presence of alien civilizations. Why would a civilization want to broadcast its presence? In Benford et al. (2010), a variety of motives were considered, but many of them are of a sociological or anthropological origin, such as a call for help, a desire to proclaim the technological achievements of a civilization, etc. Although these possibilities cannot (and ought not) be ruled out, there are some inherent difficulties. They rely on complex (anthropocentric) reasons to some degree, and are thus not easily testable. Moreover, equation (5) demonstrates that a power of $10^{25}\,\mathrm{erg\,s^{-1}}$ is required, which represents a fairly high expenditure. Hence, it seems rather implausible that all of this power would be expended on merely broadcasting a civilization's existence.

Instead, we consider the idea briefly discussed in Benford et al. (2010), and further elaborated in Guillochon & Loeb (2015) and Benford & Benford (2016) (see also Manchester & Loeb 2016), that these beams may be used for powering light sails. Let us suppose that a civilization wishes to construct a light sail capable of attaining mildly relativistic speeds. In Guillochon & Loeb (2015), it was argued that the most efficient strategy for achieving the largest possible velocity for a limited acceleration value leads to

$$v_{\mathrm{max}} = \sqrt{2 a_{\mathrm{max}} d_F}, \tag{9}$$

where v_{max} and a_{max} are the maximum velocity and acceleration respectively, whilst $d_F = \nu D^2/c$ is the Fresnel distance. The above expression takes advantage of the constant beam diameter in the near-field Fresnel region (with the sail size matching D) out to d_F, where the beam enters the Fraunhofer (far-field) regime and starts to diverge with an opening angle θ. In Section 2.1, we argued that D should be normalized in units of 3×10^9 cm for a multitude of reasons; this amounts to $d_F \sim 0.1\,\mathrm{pc}$. Using this value along with the characteristic values for v_{max} and a_{max}, we arrive at

$$\nu = 1.5\,\mathrm{GHz}\left(\frac{v_{\mathrm{max}}}{c}\right)^{2}\left(\frac{a_{\mathrm{max}}}{1\,\mathrm{gee}}\right)^{-1}\left(\frac{D}{3\times10^{9}\,\mathrm{cm}}\right)^{-2}, \tag{10}$$

having normalized the acceleration in the anthropic units of 1 gee. Remarkably, the above frequency coincides with characteristic value of 1 GHz considered thus far. In turn, this implies that the beam frequency that is optimal for powering the light sail falls within the range of FRB frequencies. Thus, it seems quite reasonable to hypothesize that the beams are being used to power light sails. We shall explore some of the ensuing implications in the next section.

3. DISCUSSION

Next, we delve into some of the other consequences arising from our prior analysis.

3.1. *The angular velocity of the beam*

Hitherto, we have not discussed any of the temporal aspects of the beam. We begin by noting that FRBs are detected as pulses with a duration Δt that is typically milliseconds. Suppose that the beam sweeps across the sky with an angular velocity Ω. The value of Ω is related to Δt via

$$\frac{\eta c}{\nu D} = \theta = \Omega \Delta t. \tag{11}$$

Alternatively, we can introduce the time period $\tau = 2\pi/\Omega$, which can be determined from the above formula, and is given by

$$\tau = \frac{7.3\,\mathrm{days}}{\eta}\left(\frac{\nu}{1\,\mathrm{GHz}}\right)\left(\frac{D}{3\times 10^{9}\,\mathrm{cm}}\right)\left(\frac{\Delta t}{1\,\mathrm{ms}}\right). \tag{12}$$

Thus, for characteristic values of the above parameters, the beam has an angular velocity of 10^{-5} rad/s and has a time period of approximately one week.

The derived sweep time of the beam direction reflects the spin or orbital motion of the beamer footprint relative to the receding sail (which cause the direction of the beam to change relative to the observer).

3.2. *On the dimensions of the potential solar sail*

The total beam power required for driving a sail of total mass m_s and maximum acceleration $a_{\max}$ can be easily computed, assuming that the reflectivity is perfect (Benford 2013; Guillochon & Loeb 2015).

$$P = 3\times 10^{25}\,\mathrm{erg\,s^{-1}}\left(\frac{m_s}{2\times 10^{6}\,\mathrm{tons}}\right)\left(\frac{a_{\max}}{1\,\mathrm{gee}}\right), \tag{13}$$

and the same characteristic value of $a_{\max}$ from (10) has been utilized. Note that m_s has been normalized by that particular amount to ensure that equation (13) matches the other estimates, namely equations (5), (6) and (8).

This implies that the mass of the sail is approximately 10^6 tons. In deriving this estimate, we have assumed a rough equipartition of the total mass between the sail and the payload, implying that the latter is also $\sim 10^6$ tons. If the density of the payload is akin to that of the International Space Station, the dimensions of the payload must be of order 100 meters.

We wish to emphasize that this value is extremely high by human standards - most estimates for light sail propulsion tend to be around 1-2 orders of magnitude lower (Crawford 1990; Fu et al. 2016). Indeed, this estimate is approximately equal to the early fission-based rockets considered in the literature, which posited a total weight of up to 10^7 tons (Dyson 1968). Thus, if this beam were indeed being used to power a spaceship, the latter would possibly have to be very large - an "interstellar ark" or "world ship" of sorts, although typical designs for such models tend to favour much higher total masses of 10^{11} tons (Hein et al. 2012).

3.3. *Implications for the number of advanced civilizations*

Equation (2) and the DMs listed in the FRB catalog imply that the characteristic distance to FRBs is of order a few comoving Gpc (Petroff et al. 2016) and the survey volume is of order $\sim \frac{4\pi}{3}(3\ \mathrm{Gpc})^3 \sim 100\ \mathrm{Gpc}^3$. Since we know that there are $\sim 10^{10}$ habitable Earth-size planets in our Galaxy (Marcy et al. 2014; Dressing & Charbonneau 2015; Burke et al. 2015), and $\sim 10^{20}$ in the entire Hubble volume (Behroozi & Peeples 2015), it is fair to assume that there are $N_E \sim 10^{19}$ habitable Earth-size planets within a volume $\sim 100\ \mathrm{Gpc}^3$. Of these, suppose that a fraction f of these planets are broadcasting beams, manifested as FRBs.

Next, note that the characteristic beam solid angle is $\theta^2 = \eta^2 10^{-16}$ steradians, based on the characteristic parameters from the previous sections and Equation (3). Since the sky is comprised of 4π steradians, and there are $f \cdot N_E$ broadcasting planets, at any given point in time $\sim (10^{-16}/4\pi) f \eta^2 N_E$ beams are visible. Each beam is visible for $\Delta t \sim 1$ ms, which implies that approximately $10^{10} f \eta^2$ beams should be visible in a day. The latest estimates suggest that there are $\mathcal{O}\left(10^4\right)$ FRBs per day (Scholz et al. 2016). If we posit that not *every* FRB arises from extragalactic civilizations, then we find,

$$f\eta^2 \leq 10^{-6}. \tag{14}$$

In principle, it should be possible to distinguish between FRBs of natural and artificial (light sail) origin. This differentiation could be made based on the expected shape of the pulse, as the beam sweeps by to power the light sail; see the detailed discussion in Guillochon & Loeb (2015). Hence, looking for similar signatures in the signal would help determine whether FRBs are powered by extragalactic civilizations (although the use of a broad range of frequencies might smear these signals). More specifically, the sail would cast a moving shadow on the observed beam, thereby leading to multiple peaks in the light curve depending on the sail geometry (Manchester & Loeb 2016).

Since we know, by definition, that $\eta \geq 1$, we arrive at the conclusion that $f \leq 10^{-6}$. If each civilization broadcasts only a single beam, this allows us to place a bound on the number of technologically sophisticated civilizations. Using this value of f in conjunction with the fact that there are $\sim 10^{10}$ habitable Earth-size planets in our Galaxy leads us to the conclusion that there are less than 10^4 FRB-producing civilizations in a galaxy similar to our own. These civilizations must be slightly more advanced than the Kardashev I type (Kardashev 1964),[2] as seen from the characteristic power required in equation (5). Although these estimates are undoubtedly on the higher side, they are consistent with the earlier, more optimistic studies involving the famous Drake equation (Drake & Sobel 1992); some of the current theories have also yielded similar values (Forgan 2009; Lingam 2016).

We reiterate that the range derived above is the *upper bound*. There are at least three factors which can lower this value:

- It is possible that the beam angle is not diffraction limited. Even a fairly modest choice of $\eta \approx 3$ can lower the value of $f_{\rm max}$ by an order of magnitude, as evident from (14).
- Not all FRBs have an artificial origin - only a fraction of them may correspond to alien activity. As an example, perhaps, one may need to single out only those FRBs that repeat, such as FRB 121102 (Maoz et al. 2015; Spitler et al. 2016).
- A civilization may have set up more than one beam emitter. Although it may seem unlikely, this could very well happen if a civilization has progressed to the Kardashev II or III stages.

In this context, an interesting corollary also follows. Since we have assumed that FRBs are of planetary origin, it is evident that the rate of FRBs is therefore set by the number of planets with advanced civilizations. This is in contrast to other models of FRBs, such as gamma-ray bursts (Zhang 2014; DeLaunay et al. 2016), whose occurrence rate is determined by the formation rate of massive stars.

Another point worth bearing in mind is that astrophysical explosions tend to produce single bursts, while artificial beacons could repeat, as observed in FRB 121102 (Spitler et al. 2016; Scholz et al. 2016).

3.4. *Looking beyond FRBs*

In our analysis thus far, we have explicitly worked with parameters that were characteristic of FRBs, such as $S_\nu \sim 1$ Jy. Now, suppose that all other quantities were held fixed in equation (4), except for the power which is lowered significantly. This amounts to stating that the observed spectral flux density could be much smaller.

What are the ramifications of using a lower value of P? If we still assume that the beam is powering a light sail, equation (13) implies that the light sail's mass or its maximum acceleration would be lower. In turn, this would imply that the spacecraft would not be capable of interstellar travel on short timescales; instead, it would be more likely to operate over *interplanetary* distances. Hence, this brings us to an important point: there may be a large number of interplanetary spacecrafts operating at extragalactic distances, which are simply too faint to be detected. In contrast, such spacecrafts and the beams powering them *within* our Galaxy are likely to be detectable (Guillochon & Loeb 2015).

Finally, we end our discussion with an interesting observation. There are approximately 10^9 $L_\star$ galaxies within 100 Gpc^3, and approximately 10^4 FRBs per day, as discussed in Section 3.3. Thus, each Galaxy has a probability of 10^{-5} FRBs/day. Hence, if we wait for 10^5 days ≈ 300 years, we may detect an FRB emanating from our own Galaxy. Note that this prediction does not rely whatsoever on the nature of the source, and is purely a statistical estimate. A Galactic FRB at a distance of 10-20 kpc would be truly spectacular since the expected value of S_ν would be 10^{10}-10^{11} Jy. If detected, it could reveal everything that can be known about the true origin of FRBs, and thereby settle this FRB origin debate once and for all.

4. CONCLUSIONS

In this Letter, we have posited that Fast Radio Bursts are beams set up by extragalactic civilizations to potentially power light sails.

In Section 2, we showed that the FRB parameters were consistent with the assumption that they are artificial beams. Along the way, we also demonstrated that there was a "natural" size for the emitter, and that it was approximately twice the diameter of the Earth. This value was arrived at by adopting two contrasting estimates - the first from energy considerations, whilst the second was obtained through engineering constraints. Subsequently, we illustrated that the frequency needed to power the light sail was consistent with those observed for FRBs, lending further credence to our hypothesis.

Our analysis gave rise to many interesting consequences. In Section 3, it was shown that the payload of the light sail must be approximately 10^6 tons, and that the beam has a characteristic period of approximately 1 week. Moreover, under certain simplifying assumptions, in Section 3.3, we derived an upper bound on the total number of intelligent civilizations in a galaxy (akin to the Milky Way). We also suggested that there may be a potentially large number of smaller light sails which are presently undetectable as their spectral flux densities are too low. Using the all sky cosmological rate of FRBs, we argued that an FRB might originate within the Milky Way once every several centuries, and the striking Galactic event could be utilized in improving our understanding of FRBs.

Although the possibility that FRBs are produced by extragalactic civilizations is more speculative than an astrophysical origin, quantifying the requirements necessary for an artificial origin serves, at the very least,

[2] Recently, extensive studies have been undertaken which place stringent constraints on the number of Kardashev III civilizations (Wright et al. 2014; Zackrisson et al. 2015; Griffith et al. 2015).

the important purpose of enabling astronomers to rule it out with future data.

We thank James Guillochon, Zac Manchester and Dani Maoz for their helpful comments. This work was supported in part by a grant from the Breakthrough Prize Foundation for the Starshot Initiative.

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